

SCREENING OF POTENTIAL LANDING GEAR NOISE CONTROL DEVICES AT VIRGINIA TECH FOR QTD II FLIGHT TEST

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In support of the QTD II (Quiet Technology Demonstrator) program, aeroacoustic measurements of a 26%-scale, Boeing 777 main landing gear model were conducted in the Virginia Tech Stability Tunnel. The objective of these measurements was to perform risk mitigation studies on noise control devices for a flight test performed at Glasgow, Montana in 2005. The noise control devices were designed to target the primary main gear noise sources as observed in several previous tests. To accomplish this task, devices to reduce noise were built using stereo lithography for landing gear components such as the brakes, the forward cable harness, the shock strut, the door/strut gap and the lower truck. The most promising device was down selected from test results. In subsequent stages, the initial design of the selected lower truck fairing was improved to account for all the implementation constraints encountered in the full-scale airplane. The redesigned truck fairing was then retested to assess the impact of the modifications on the noise reduction potential. From extensive acoustic measurements obtained using a 63-element microphone phased array, acoustic source maps and integrated spectra were generated in order to estimate the noise reduction achievable with each device.

I. Introduction

Aeroacoustic measurements of a 26%-scale, Boeing 777 main landing gear model at the Virginia Tech Stability Wind Tunnel were started in 2002 as part of a NASA contract¹. Beginning in 2004, Virginia Tech provided support to the QTD II (Quiet Technology Demonstrator) program, a joint effort by Boeing Commercial Airplanes, NASA, Goodrich Corporation, General Electric, and All Nippon Airways^{2,3}. Under the airframe noise element of the program, one of the objectives of this partnership was the experimental screening of different noise control concepts for a Boeing 777 main landing gear being considered for a flight test to be performed in Glasgow, Montana in 2005.

For this effort, several noise control devices were designed by Goodrich and Boeing⁴ and extensively tested at Virginia Tech. In the preliminary phase, noise control devices were designed and manufactured in stereo-lithography for the gear components that were determined to be the most dominant in terms of their contribution to the overall noise levels^{1,5,6}. In this regard, devices to reduce noise were built for the cable harness, the door/strut gap, the shock strut, the wheel brakes and the lower truck. In the case of the lower truck fairing, also referred to as the “toboggan” fairing, different designs of varying width and forward section shape were evaluated in order to determine the impact on the noise emission for each of these parameters. The devices were tested in multiple configurations including combinations of devices, different truck angles, and several flow speeds.

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As a result of the preliminary testing of these devices, a new design for the lower truck fairing was achieved, constructed, and subsequently tested. The new design took into account installation constraints, such as tire deflection and brake cooling effects. Given the promising results obtained in wind tunnel testing, the improved lower truck fairing was constructed and tested during the QTD II flight test⁷.

Aeroacoustic measurements were performed with a 63-element microphone phased array. The array consists of a multi-arm spiral using Panasonic Electret microphones coupled with a conditioning circuit developed at NASA Langley Research Center by Humphreys and Shams et al.⁸. Results for several noise control devices are presented using acoustic maps and integrated spectra as rendered from conventional beamforming processing. Such results are compared to those of the baseline landing gear (i.e. with no noise control devices installed) in order to quantify the noise reduction potential of each device as well as combinations of them.

This work serves as an introduction to a series of papers related to airframe noise reduction efforts under the QTD II program. The goal of this set of papers is to show the complete process, from design to wind tunnel testing, that led to the full scale implementation of a noise control device in the flight test performed in Glasgow, Montana in 2005. In this sense, the design and analysis of the full-scale device by Goodrich⁴ and the airframe noise results from the QTD II program, to be presented by Boeing⁷, will complete the mentioned process.

II. Experimental Setup

This section describes the experimental setup for the tests conducted at Virginia Tech (VT). For this purpose, descriptions are provided for the wind tunnel, the landing gear model, and the microphone phased array.

A. Wind Tunnel Facility

The experiments presented in this work were conducted at the Virginia Tech Stability Wind Tunnel shown in Fig. 1. The facility is a continuous, closed circuit, single return, subsonic wind tunnel with a 24 ft (7.3 m) long square test section of 6 by 6 ft (1.83 by 1.83 m). The acoustic treatment of the tunnel⁹ was not in place at the time of the tests presented in this work. The tunnel is powered by a 600 hp DC motor driving a 14 ft (4.26 m) propeller providing a maximum speed of about 255 ft/s (280 km/h) for the empty wind tunnel, i.e. $M=0.23$. The main characteristics of this tunnel are a uniform flow throughout the test section and low turbulence intensity.

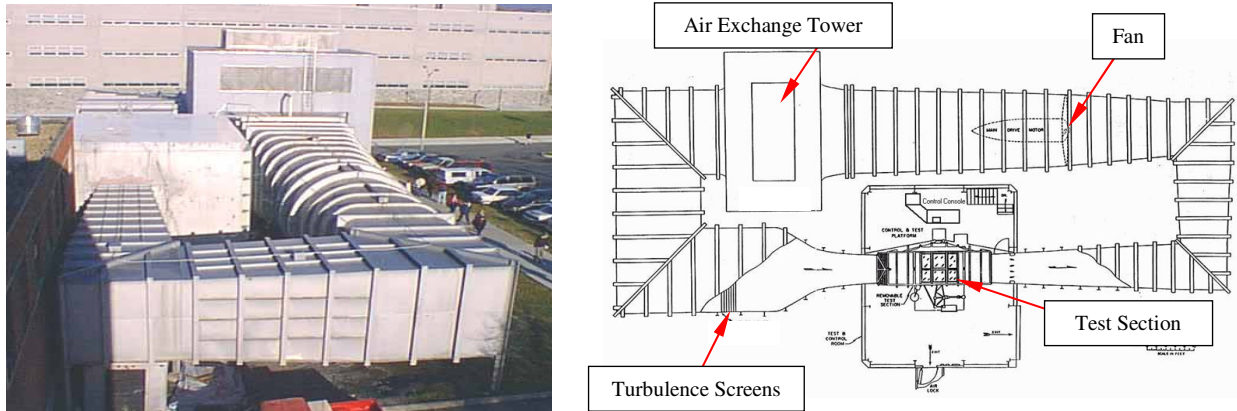


Figure 1. Picture and schematic of the Virginia Tech Stability Wind Tunnel.

B. Landing Gear Model

The high fidelity, 26%-scale, 777 main landing gear model used in this study was originally tested under the STAR (Subsonic Transport Aeroacoustic Research) program using a semi-span model of the 777 in the NASA Ames 40- by 80-ft wind tunnel⁶. The isolated gear model was also evaluated under the AST (Advance Subsonic Transport) and QAT (Quiet Aircraft Technology) programs in the NASA Ames 7- by 10-ft wind tunnel⁵. The model is shown in Figs. 2a and 2b in the actual landing position. For the current study, the model was mounted on the floor of the Stability Wind Tunnel test section, thus, the pictures are presented upside down.

The high-fidelity model features all the major gear components: strut, braces, torque link, cable harnesses, lock links, main door, and wheels. It also includes most of the details found in the full-scale landing gear, including: oleo lines, cables, wheel hubs, brake cylinders, and hydraulic valves. The main structure of the model is made of steel and aluminum and the details are mostly made in stereo lithography up to an accuracy of 3mm in full-scale. The main differences with the actual landing gear are: the wheel hubs do not have the openings that allow air to flow freely through the wheels, a smaller door located close to the wing and attached to the main door is not in the model, and the wing cavity is not modeled.

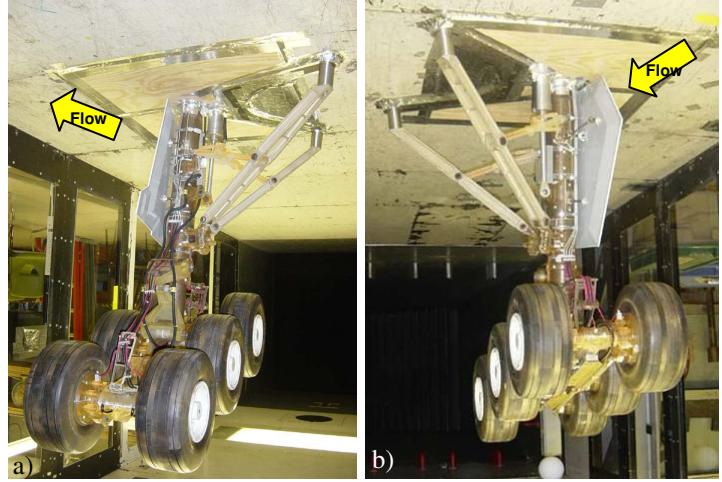


Figure 2. High fidelity 26%-scale 777 main landing gear model: a) rear and b) front view.

C. Microphone Phased Array

A 63-element microphone phased array was developed using Panasonic Electret microphones coupled with a conditioning circuit developed by NASA¹⁰. The pattern of this array is an equal-aperture, multi-arm spiral designed for VT by J. Underbrink and R. Stoker from the Boeing Company. Figure 3 shows a picture of the array and the positioning of the sensors. Sample array responses using conventional beamforming¹¹⁻¹³ are shown in Fig. 4. The beamwidth of this array for a plane parallel to the array at 36" (i.e. similar to testing conditions in the tunnel) is given by $BW_{36"} = 2.45 \lambda$, and the Signal-to-Noise Ratio (SNR) is at least 10 dB. Although the array was designed in a nested array configuration, the processing shown in this work includes all microphones. For each configuration, the beamforming results for forty-five 1/12th octave bands (band numbers 132 through 176) were computed. These bands correspond to center frequencies from 2 to 25 kHz at model scale. However, the anti-aliasing filter of the data acquisition system was set to 20 kHz. This action was instigated by the fact that the phased array microphones were found to provide reliable levels only up to about 20 kHz. As reported by Humphreys et al.¹⁰, the microphone response is not flat above this frequency. However, as long as the phase is matched, the beamforming maps should still be accurate in terms of identifying noise sources. Furthermore, this study was mainly concerned with differences in levels when compared to a baseline configuration and, as such, would not be affected by a non-flat response of the microphones.

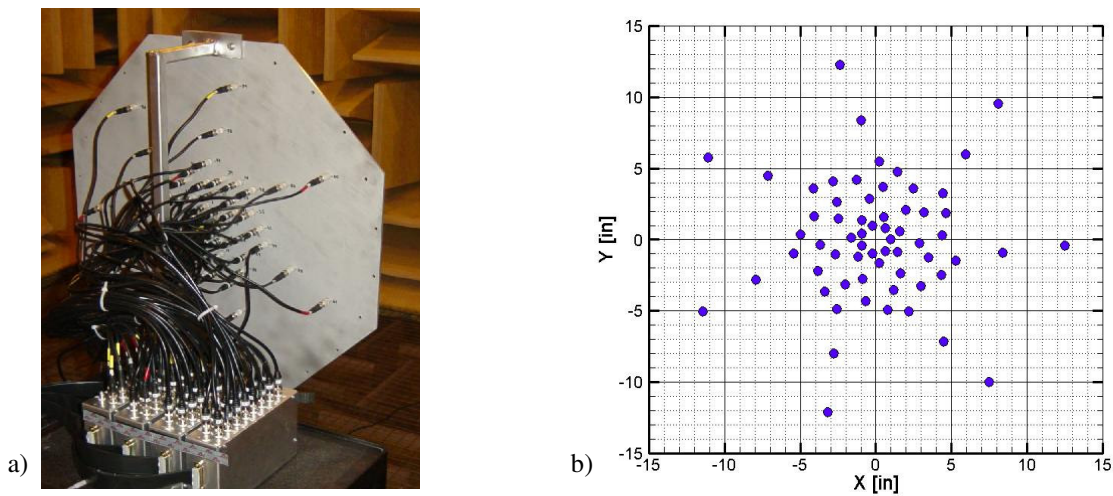


Figure 3. 63-element multi-arm spiral VT phased array. a) Picture of the array, and b) microphone locations.

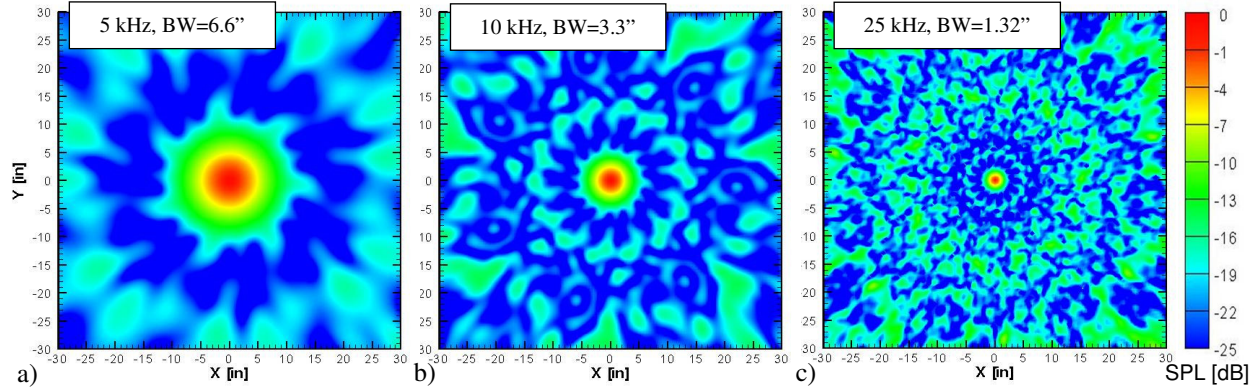


Figure 4. 63-element phased array response for a) 5, b) 10, and c) 25 kHz in a plane 36" from the array.

For aircraft certification purposes, the noise emitted by the aircraft towards an observer in the flyover path is the most important component. However, if only a phased array in the flyover position were used for the measurements, most of the noise sources would not be identified accurately since they would be shielded by the truck and wheels. The shielding blocks the direct path of propagation assumed in the beamforming algorithm. To avoid this problem, two different array positions were used. The phased array was mounted in the ceiling of the wind tunnel and close to the truck as indicated in Fig. 5a. In addition, the array was installed in one of the walls of the wind tunnel, on the braces side, as shown in Fig. 5b. Only results with the array in the flyover path are shown in this work.

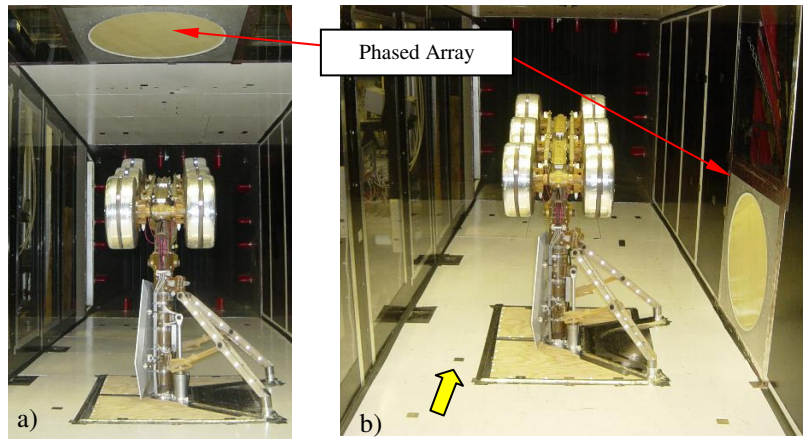


Figure 5. Phased array mounted on a) flyover, and b) braces side of the landing gear model.

To account for flow effects, a simple correction for convection was performed based on a test using a speaker at the center of the test section and estimations based on the Green's function for a monopole with flow. As a result, a uniform "shifting" of the maps was performed. As reported in the literature⁸, applying shear layer corrections should improve the beamforming results in terms of increasing correlation. However, such corrections were not applied to obtain the results presented in this work.

To avoid the hydrodynamic noise induced over the array microphones by the turbulence in the boundary layer of the wind tunnel, the microphones were recessed behind a stretched Kevlar cloth. This mounting technique was developed and tested at NASA Ames¹⁴. Since Kevlar can be considered acoustically transparent in the frequency range of interest (i.e. up to 20 kHz), the pressure fluctuations on the microphones due to the boundary layer unsteadiness are significantly reduced while allowing the sound to propagate through the cloth¹⁴. None the less, given the high tension applied while stretching the cloth, the Kevlar appears as a hard surface to the flow.

III. Noise Control Devices

As mentioned before, the noise control devices tested at Virginia Tech were designed by Goodrich and Boeing⁴ and targeted the most dominant noise sources in terms of their contribution to the overall noise levels as determined from previous wind tunnel testing^{1,5,6}. The components most responsible for the noise include the cable harness, the door/strut gap, the shock strut, the wheel brakes and the lower truck.

In order to mitigate the noise from the cable harness, a “bull-nose” fairing was designed as a means to “streamline” the flow around such a component (Fig. 6). This device showed no significant noise reduction in the flyover direction. Hence, results for this device are not presented in this paper.

To reduce the noise from the door/strut gap and the components in the shock strut region, a fairing was designed to plug the gap and cover the upper frontal section of the strut, as shown in Fig. 7. Design constraints such as gear retraction were taken into account to avoid interference in all phases of gear operation.

To eliminate the noise sources emanating from the brake cylinders, a fairing was designed to cover the brake’s finer structures and thus streamline the highly interactive flow field. As shown in Fig. 8, depending on the axle, a different design was implemented. Given that this design only covered the section exposed to the flow, it still allowed for convective cooling of the brakes.

In the case of the lower truck fairing, also referred to as the “toboggan” fairing, different designs were tested in terms of width and forward section coverage in order to determine the impact of each of these design parameters on the noise emission. In terms of the forward or upstream section coverage, two distinct segments corresponding to 90° and 180° arcs were tested. Figure 9b shows the toboggan fairing with both forward segments. Figure 9c shows the toboggan with the 90° forward arc installed on the landing gear. The extension of the forward segment from 90° to 180° provided little noise benefit. Therefore, only results for the 90° arc are presented in this paper. To determine the noise benefits associated with extending the toboggan width, three different designs that were referred to as minimum, medium, and maximum width were tested. Such designs are shown in Fig. 10. The minimum width toboggan was designed to extend up to the brake cylinders, allowing air to flow to the brakes and not impacting convective cooling. The medium width toboggan design extended the coverage to include the brake cylinders. This design was determined to be a good choice in terms of maintaining safe clearance from the tires and other truck components while maximizing the width. The maximum width toboggan design was an impractical design in terms of implementation on the full scale gear and was tested only to determine the maximum noise reduction achievable with a toboggan type fairing.

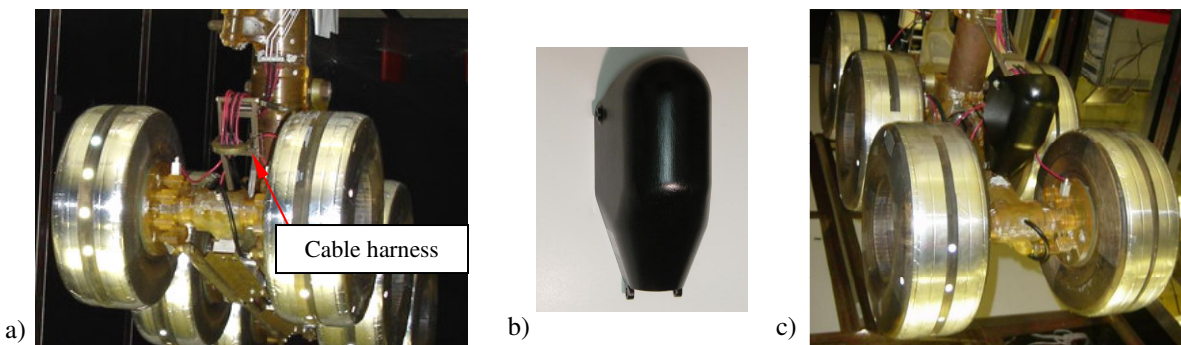


Figure 6. a) Detail of baseline gear, b) “Bull-nose” fairing for front cable harness, and c) fairing installed.

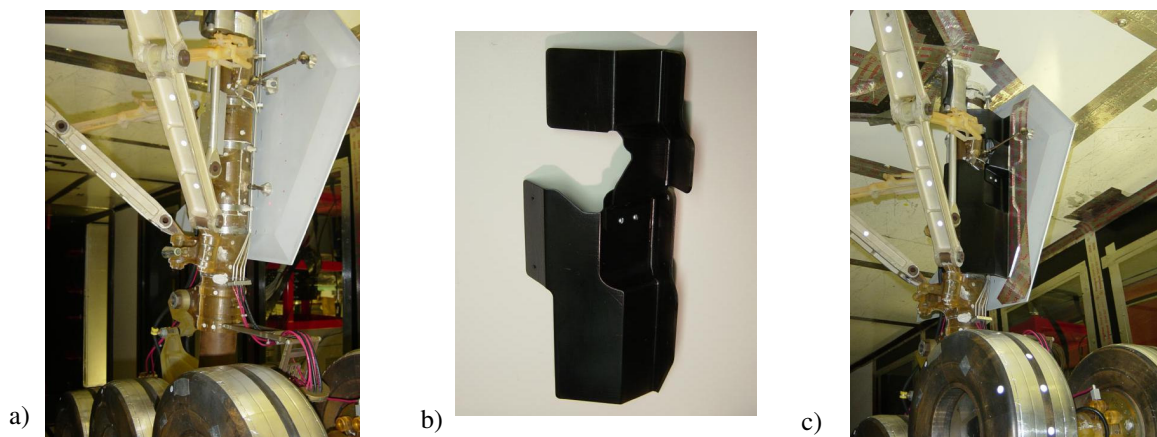


Figure 7. a) Detail of baseline gear, b) shock strut fairing, and c) fairing installed.

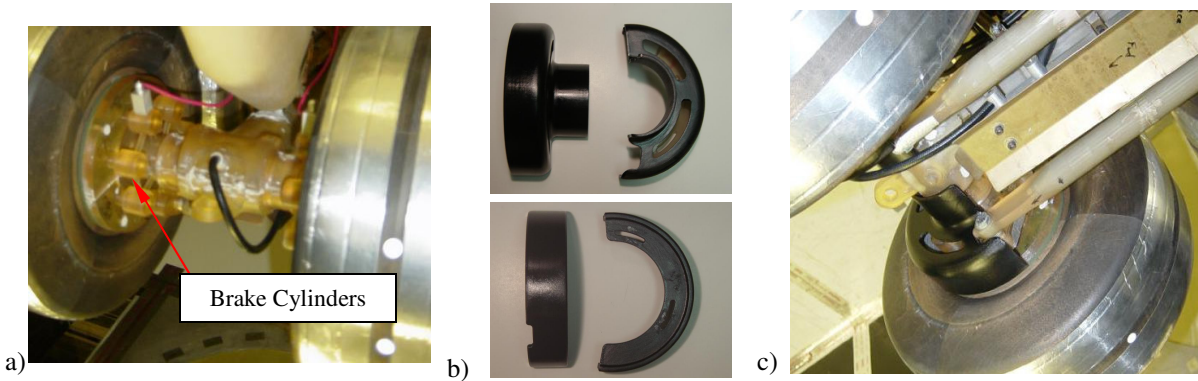


Figure 8. a) Detail of baseline gear showing the brake cylinders, b) brake fairings, and c) fairings installed.

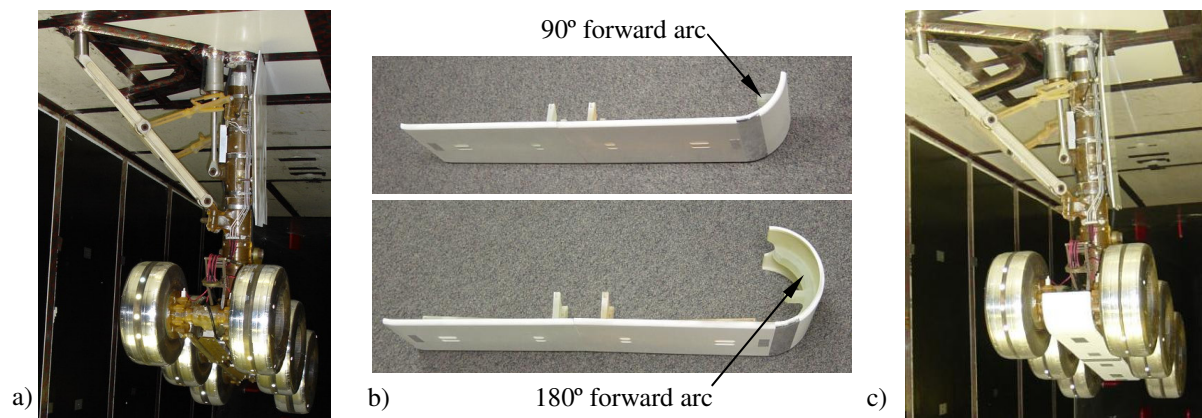


Figure 9. a) Baseline gear, b) lower truck fairing (“toboggan”), and c) fairing installed.

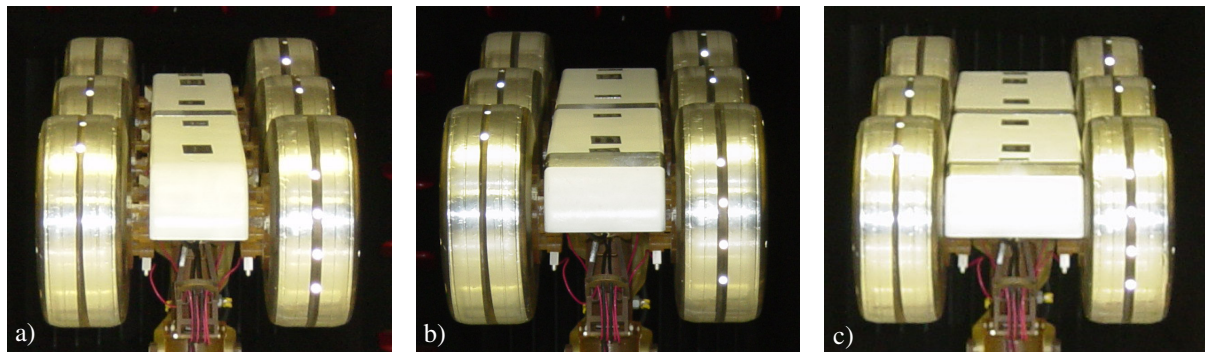


Figure 10. a) Minimum, b) medium, and c) maximum width “toboggan” fairing

An alternative concept (independent of the fairings described above) for “streamlining” the flow around the gear truck involved changing the alignment of the lower truck from a typical “toes-up” inclination (about 13 degrees) to 0 degrees inclination with respect to the incoming local flow.

Several combinations of noise control devices were also tested as well as different flow speeds and truck angles.

Based on the test results that will be presented in the next section, a modified (near final design) version of the toboggan fairing was retested in a later stage. The goal was to implement a fairing that would possess the attributes of the maximum width toboggan (provide maximum noise reduction) while accounting for implementation issues in full scale, i.e. tire deflection and brake cooling effects. To this end, the minimum width toboggan was modified using a silicone elastomer with a polyester/fiberglass stiffening element inserted to extend it as close as possible to the tires without compromising functionality. The width of this redesigned fairing falls in between the medium and

maximum toboggan widths. A schematic of the device and a picture of its installation on the model are shown in Fig. 11. Design and construction details for the toboggan fairing that eventually was flight tested can be found in the paper by Abeysinghe et al.⁴

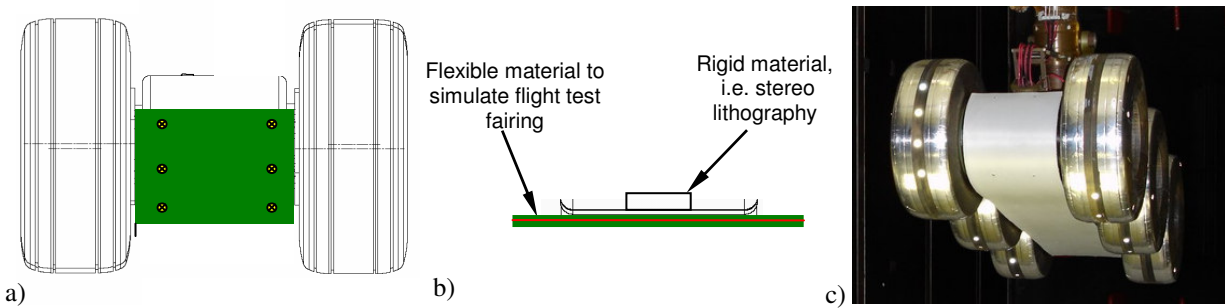


Figure 11. a) Front view, b) section schematic, and c) picture of installed “flight test” toboggan fairing.

IV. Analysis of Results

This section discusses the most significant results that led to the down selection of the toboggan fairing as the most promising concept and the device to be flight tested. Since several configurations were tested, attention is focused only on those devices/configurations that were used to quantify the performance of the final design.

The analyzed results will be presented using maps of acoustic source strength and deltas in integrated noise levels¹¹ with respect to a baseline landing gear configuration, i.e. no noise control devices. Although acoustic results showed very good data repeatability (even for measurements that were conducted many months apart), the results for various gear configurations were compared to their respective baseline acquired in the same test entry. The results are presented in model-scale frequencies.

A. Acoustic Maps

Figure 12 shows a comparison of the acoustic maps for different noise control devices for a $1/12^{\text{th}}$ octave band with center frequency of 3.65 kHz. All levels are referenced to the peak in the baseline configuration across the entire scanning region. Figure 12a provides the baseline configuration map that shows noise sources at the front and rear brakes as well as a noise source between the front and center wheel. Figure 12b shows the result of using brake fairings on all 6 wheels. With the addition of brake fairings, noise radiation increases in the front brake area (about 1 dB) and it decreases in the rear brake area. This type of result using brake fairings was found for low frequencies and will be more noticeable when analyzing the integrated spectra. Figure 12c shows the acoustic map for the minimum width toboggan where noise reduction is observed in the front brake area. This device did not show significant noise reduction in the rear brake area for low frequencies, i.e. below 4 kHz. It is worth pointing out that the noise source between the front and center wheels is still present, suggesting that such a source is from a component in the strut.

Figure 13a shows the acoustic map for a combination of the minimum width toboggan and brake fairings. As can be seen, the noise in the brake area is reduced when compared to the baseline configuration of Fig. 12a. The noise reduction efficacy of such a combination is more significant at higher frequencies as will be shown later. Note that the strut source is still present. To demonstrate that this source is emanating from the strut, Fig. 13b shows the results when the strut fairings are added to the gear in conjunction with the toboggan and brake fairings. As can be seen, the noise source between the wheels is reduced, confirming that it is related to a component in the strut.

Figure 14 shows a comparison of the acoustic maps for the minimum width toboggan and the brake fairings for a $1/12^{\text{th}}$ octave band with center frequency of 8.2 kHz. Note that in these maps, the noise reduction is more significant in the truck and brake areas. This is a trend found for frequencies between 5 and 20 kHz. Also, notice that for higher frequencies, the toboggan fairing reduces the noise radiated by the brakes in the flyover direction.

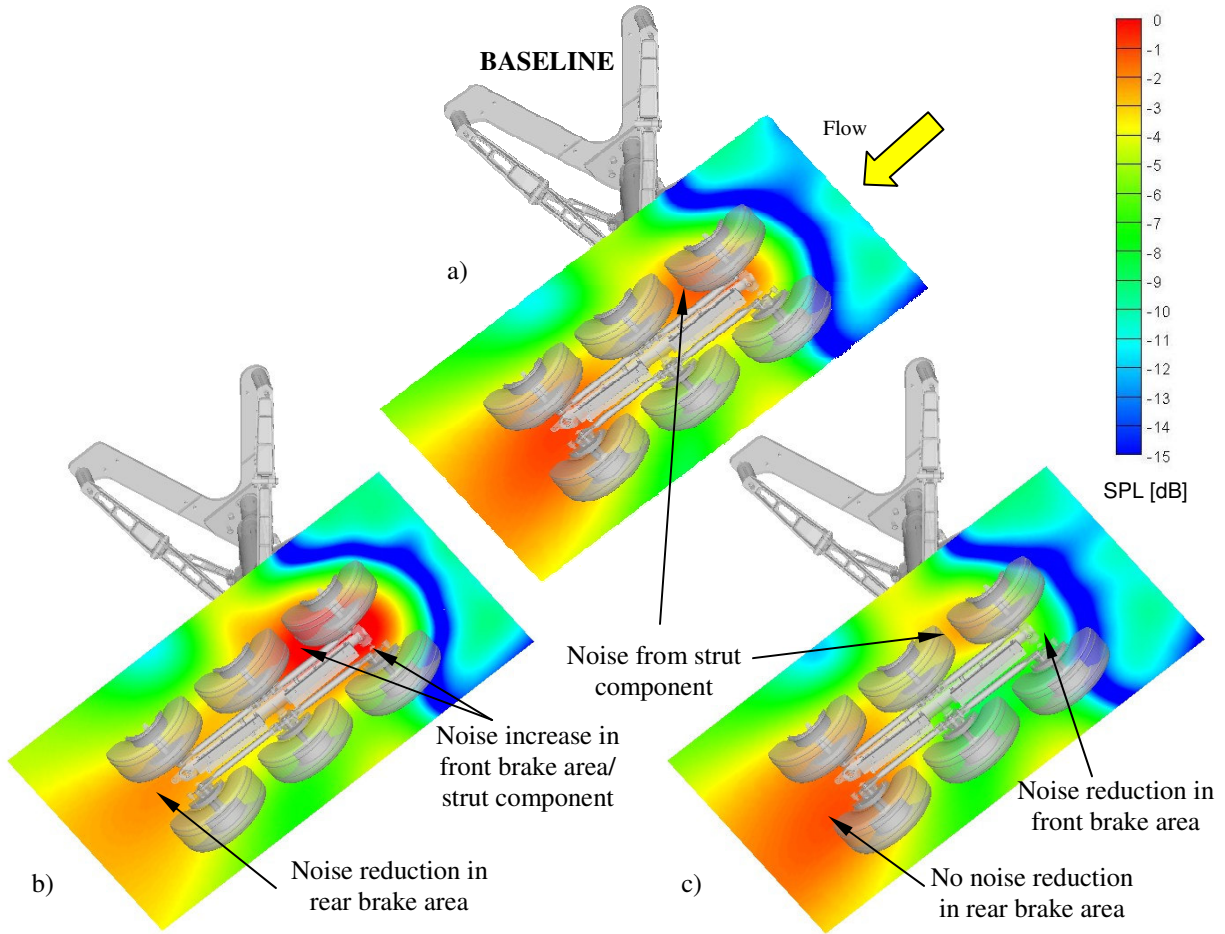


Figure 12. Acoustic maps comparison at 3.65 kHz: a) baseline, b) brake fairings, and c) minimum width toboggan fairing

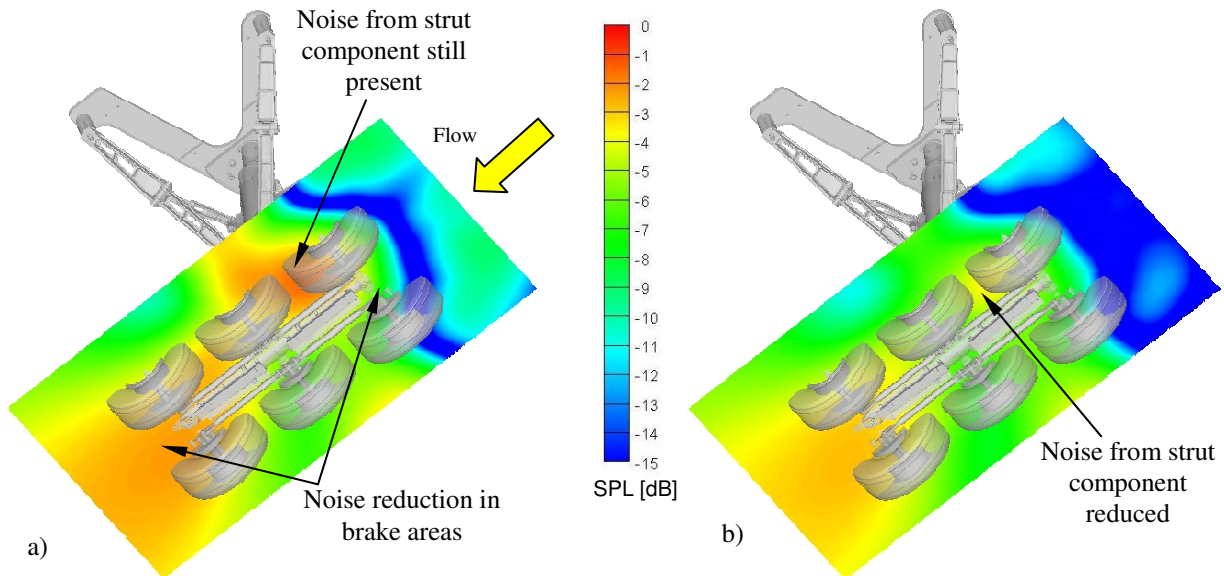


Figure 13. Acoustic maps comparison at 3.65 kHz: a) combination of minimum width toboggan and brake fairings, and b) same configuration plus strut fairings

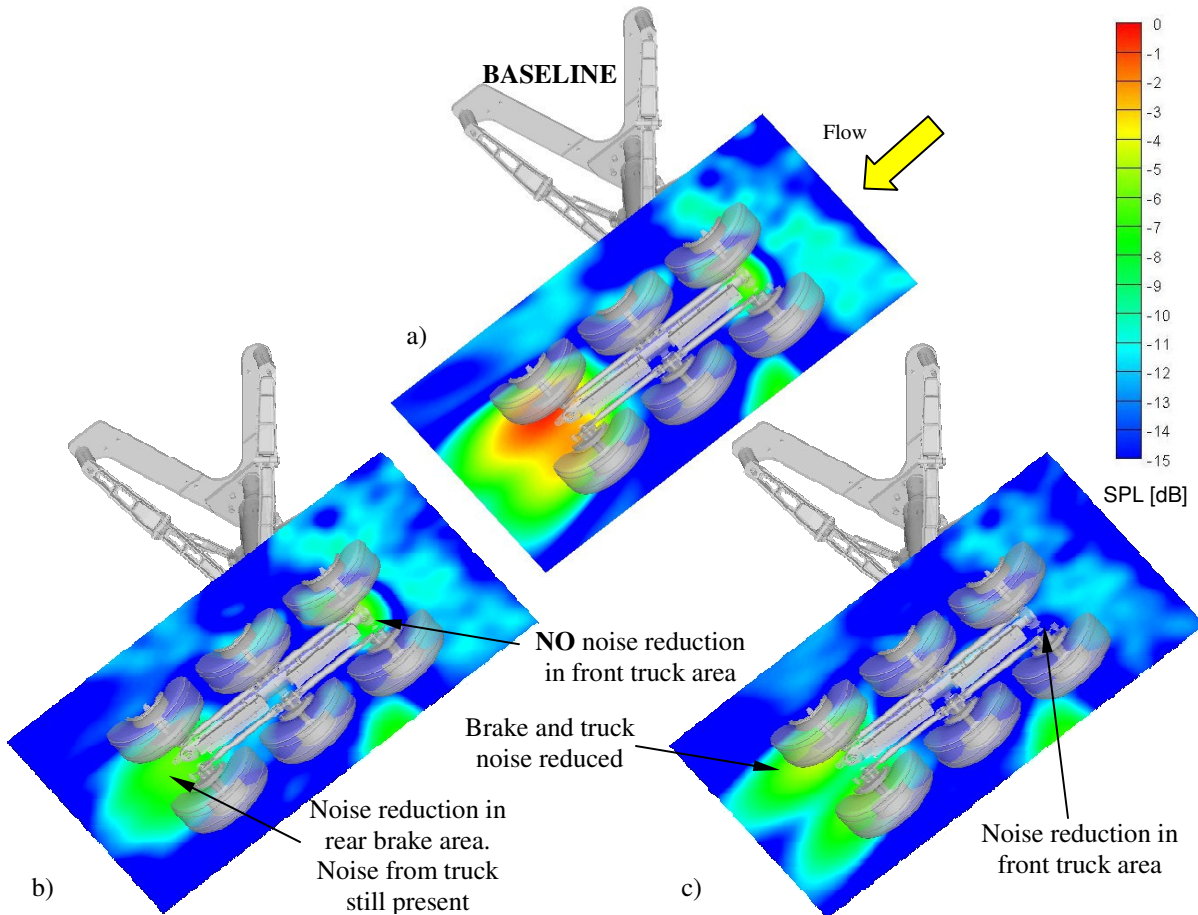


Figure 14. Acoustic maps comparison at 8.2 kHz: a) baseline, b) brake fairings, and c) minimum width toboggan fairing

Figure 15 shows a comparison between the minimum width toboggan and brake fairings that were installed separately and in combination, for a 1/12th octave band with center frequency of 8.2 kHz. In this case, the data for the toboggan and brake fairings are the same as in Fig. 14, but the contour map coloring has been modified in order to accentuate the differences. Note that the combination of the two noise control devices clearly shows a marked improvement over the results obtained from each of the concepts separately. Testing of different toboggan widths showed that the noise radiation from the brakes to the flyover path decreases as the width of the device increases. An example of such results for the maximum width toboggan is shown in Fig. 15d where the noise reduction observed is more significant than the previous combination of truck and brake devices. This suggests that brake fairings are not necessary if the toboggan is wide “enough.” This is mostly related to shielding effects by the toboggan rather than localized flow modifications as in the case of the brake fairings.

For the reason mentioned above, it was desired to have a toboggan fairing as wide as possible. However, different constraints arise for such implementation, i.e. brake cooling, tire deflection/rub, and interference with the rear wheels steering mechanism. More details on how these and other constraints were addressed in the final design can be found in the companion paper⁴ that is devoted to the description of the full scale toboggan fairing.

After several months of intense design work on the full-scale flight test article, a new toboggan fairing design was made available for testing at Virginia Tech (see Fig. 11). The new design was tested in the same facility and with the same instrumentation. Other configurations, including the baseline, were also retested. Sample acoustic maps from this entry for the baseline and “flight-test” toboggan are shown in Fig. 16 for a 1/12th octave band with a center frequency of 8.2 kHz. The corresponding results for 10.3 kHz are shown in Fig. 17. It is evident from both figures that a significant reduction in the noise radiated from the truck and rear brakes areas is achieved. This trend was observed at most frequencies.

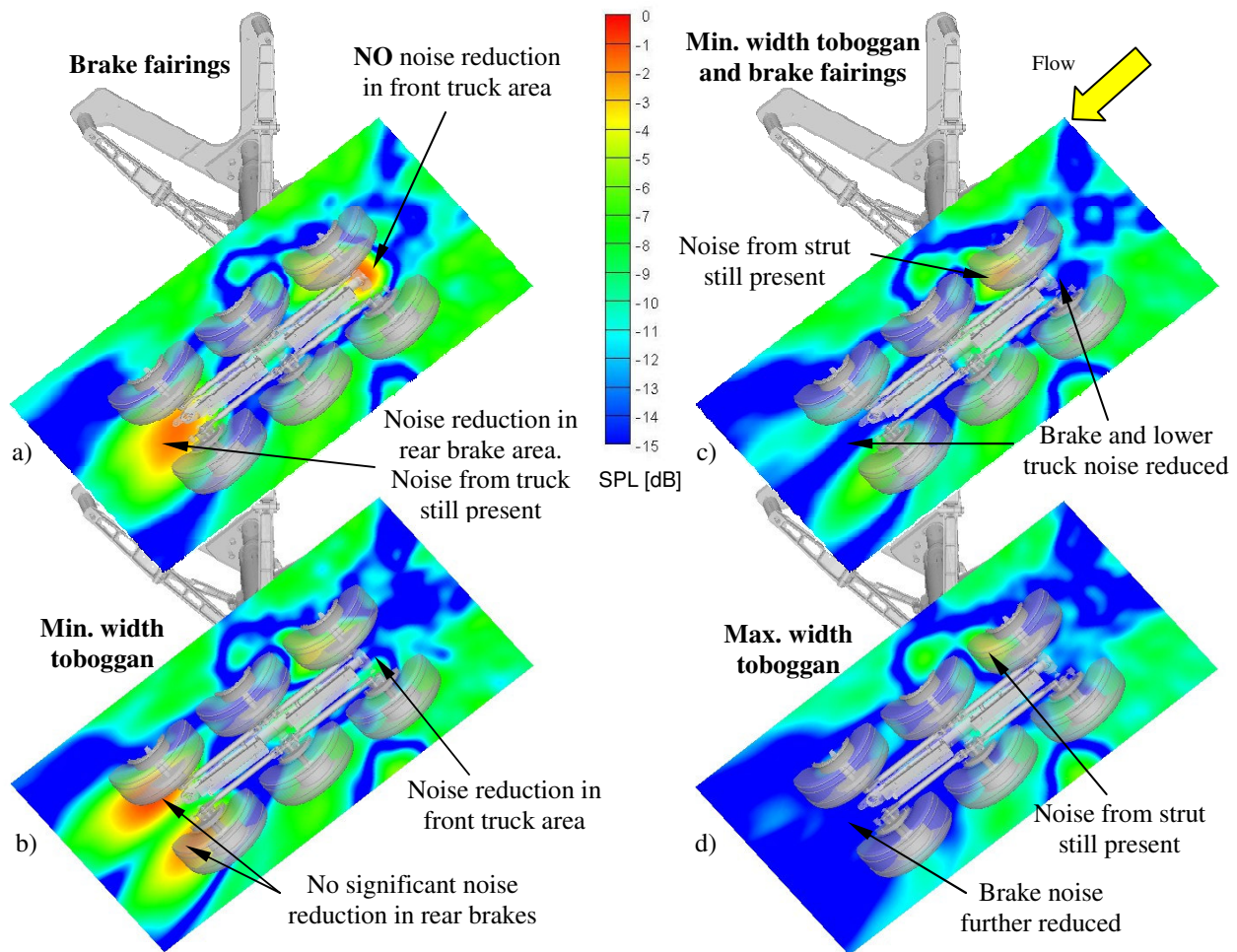


Figure 15. Acoustic maps comparison at 8.2 kHz between a) brake fairings, b) min. width toboggan fairing, c) combination of minimum width toboggan and brake fairings, and d) maximum width toboggan fairing.

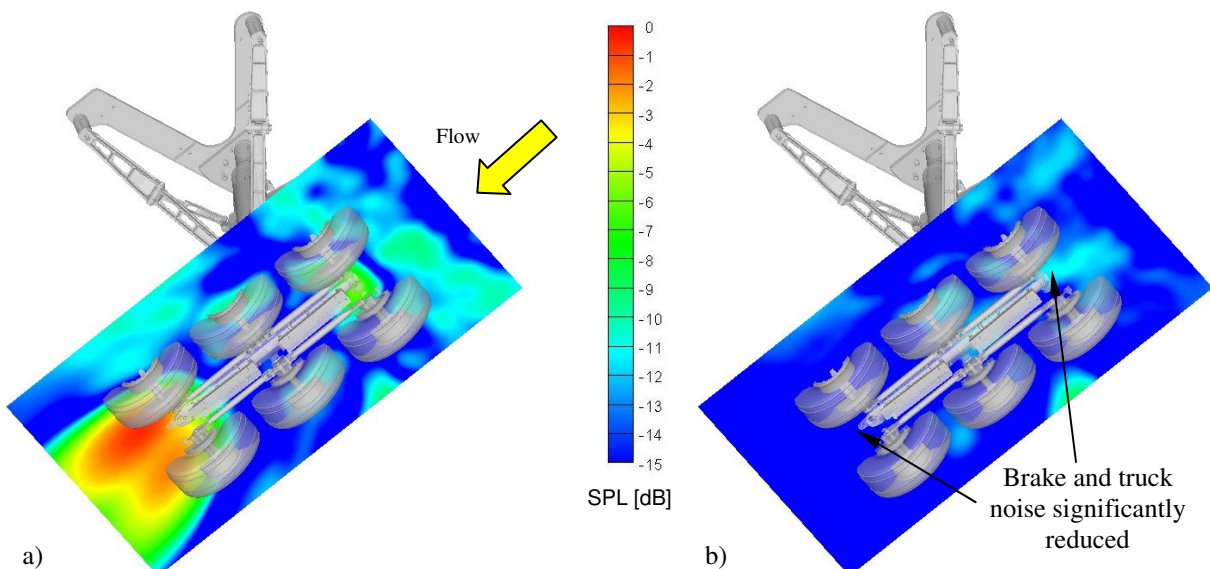


Figure 16. Acoustic maps comparison at 8.2 kHz between a) baseline landing gear, and b) flight test toboggan (model scale frequency) showing significant noise reduction.

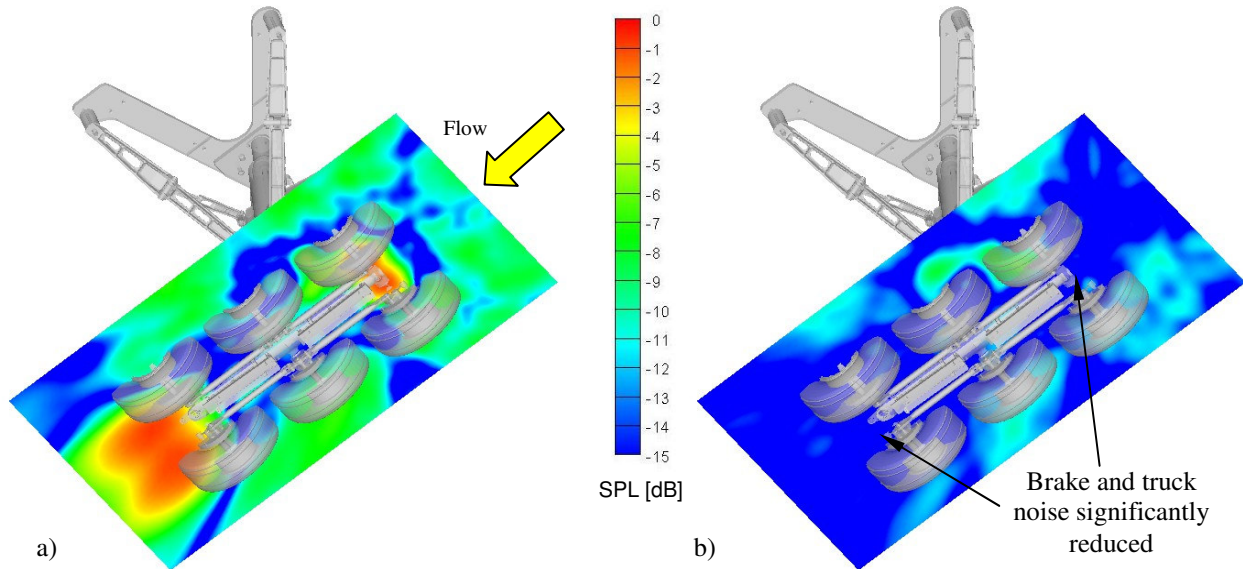


Figure 17. Acoustic maps comparison at 10.3 kHz between a) baseline landing gear, and b) flight test toboggan (model scale frequency) showing significant noise reduction.

B. Integrated Spectra Results

In order to summarize the results and compare the noise reduction potential of each device, the difference in the integrated spectra between the previously mentioned devices and the baseline landing gear will be shown next, i.e. noise reduction as a function of frequency (in model scale). To this end, the integrated spectrum of each configuration was calculated over a volume enclosing the landing gear with a threshold of 10 dB below the maximum level. The region “under” the truck was included in the integration to account for variations in the noise from sources in the main strut area. The results were normalized to account for the width of the point spread function as indicated by Dougherty¹¹.

Figure 18 shows the integrated spectra for the devices presented in the previous section. As mentioned before, it was found that the brake fairings do not provide noise reduction at low frequencies (below 4 kHz). At mid frequencies (4 to 11 kHz), this fairing shows noise reductions of about 1 to 2 dB. Above 11 kHz, the reduction is less than 1 dB. The minimum width toboggan fairing shows no noise reduction at low frequencies and reductions of 1 to 3 dB at mid frequencies. At higher frequencies, the reduction is about 1 dB. The combination of these two noise control devices (minimum width toboggan and brake fairings) behaves similarly to the toboggan only configuration below 7 kHz. However, significant improvement is obtained above 7 kHz. As the plot shows, reductions of at least 2 dB and up to 5 dB are obtained. Aligning the gear with the incoming local flow provides modest noise reduction benefits. Overall, gear alignment provides 1 dB noise reduction for frequencies below 4 kHz and between 2 dB to 3 dB for frequencies above 4 kHz. As expected, the maximum width toboggan shows an improvement in noise reduction over the combination of minimum width toboggan and brake fairings. The noise reduction is between 3 and 8 dB over most of the frequency range. As mentioned before, this last result led to redesigning the toboggan fairing in order to maximize the width while accounting for implementation constraints.

Finally, the “flight-test” toboggan results show that the noise reduction potential is comparable to that of the maximum width toboggan. For this device, reductions ranging from 3 to 8 dB are obtained in the frequency range from 4 to 20 kHz. This observed noise benefit also reinforces our earlier assertion that beyond a certain width, the shielding characteristics of the toboggan fairing render the presence of the brake fairing unbeneficial.

Note that, given the relative size of the model and the test section, these results were obtained with the phased array in the flyover position and thus relatively close to the model. Thus, it is not clear if such values correspond to actual noise reduction or the influence of decorrelation effects over the array aperture. This effect would result in lower beamforming output and thus lower integration levels, i.e. rendering in some configurations a noise reduction higher than the actual one. As suggested by Brooks and Humphreys¹³, the effect of decorrelation could be studied by processing the data in “sub-arrays”. Hence, if decorrelation effects are not significant, the integrated spectra values should not vary significantly between sub-arrays. However, no studies were carried out to resolve this point.

Recently, further testing was conducted at the acoustically-treated Virginia Tech Stability Tunnel to address the previously mentioned issues¹⁵ and those results will be published in the near future.

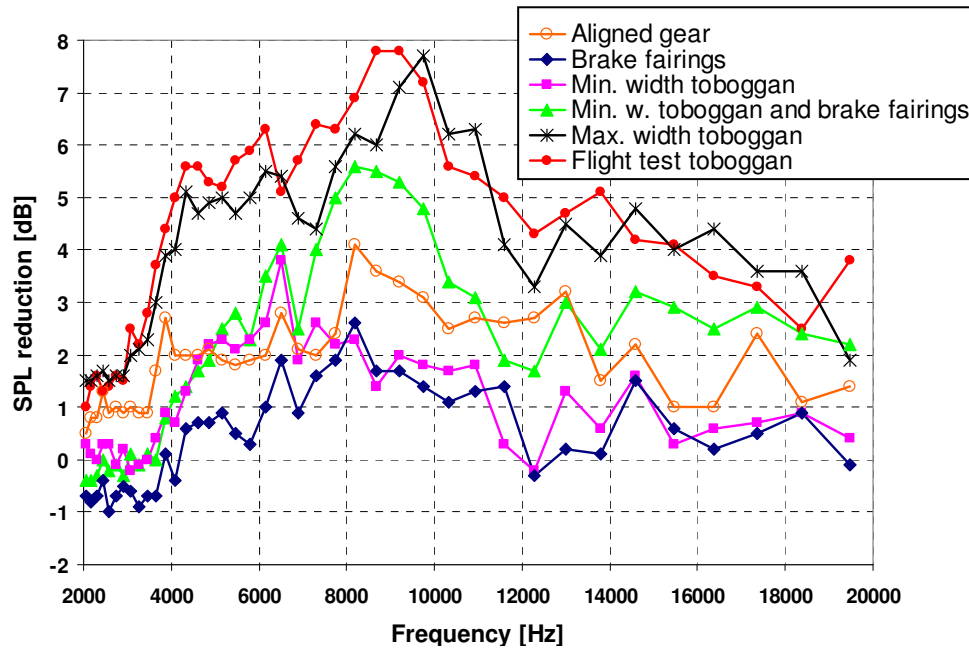


Figure 18. Integrated spectra noise reduction for different noise control devices when compared to baseline landing gear (model scale frequencies).

V. Conclusions

A series of noise control devices for a Boeing 777 main gear were tested at the Virginia Tech Stability tunnel as part of a risk mitigation study in support of the QTD II flight test program. The noise reduction devices targeted the major gear noise sources found in previous testing, i.e. the cable harness, door/strut gap, shock strut, wheel brakes and lower truck. A down selection was performed based on the aeroacoustic data obtained with a 63-element microphone phased array. As a result, the toboggan fairing was redesigned to account for implementation constraints in the full-scale gear and tested again in the same facility. The results for the redesigned fairing showed significant noise reduction in the lower truck and brake areas. It was found that the use of brake fairings is not necessary if the toboggan has the correct width, i.e. extending as close as possible to the wheels. The integrated spectra for the flight test toboggan showed noise reduction of at least 4 dB over most of the frequency range when the array was located in the flyover position. Given the promising results obtained in wind tunnel testing, this device was selected for the QTD II flight test of a Boeing 777 performed in Glasgow, Montana in 2005. The aligned gear concept was also chosen for the flight test due to the combination of modest noise reduction benefits and the relative ease of implementation.

It is noted, however, that due to the close proximity between the array and the model, decorrelation effects over the array aperture may have affected the beamforming output and thus the integrated levels, i.e. the reported noise reduction levels can not be directly extrapolated or attributed to an observer in the far field. No studies were carried in this work to quantify such effects. However, recent studies to address this issue were conducted at the renovated, acoustically-treated Virginia Tech Stability Tunnel and will be published in the near future.

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References

- ¹Patricio A. Ravetta, Ricardo A. Burdisso, Wing F. Ng, "Wind Tunnel Aeroacoustic Measurements of a 26%-scale 777 Main Landing Gear Model," *10th AIAA/CEAS Aeroacoustics Conference and Exhibit*, May 2004, Manchester, United Kingdom. AIAA 2004-2885
- ²William H. Herkes, Ronald F. Olsen, and Stefan Uellenberg, "The Quiet Technology Demonstrator Program: Flight Validation of Airplane Noise-Reduction Concepts," *12th AIAA/CEAS Aeroacoustics Conference*, May 2006, Cambridge, MA. AIAA-2006-2720
- ³Leon Brusniak, James R. Underbrink, and Robert W. Stoker, "Acoustic Imaging of Aircraft Noise Sources Using Large Aperture Phased Arrays," *12th AIAA/CEAS Aeroacoustics Conference*, May 2006, Cambridge, MA. AIAA 2006-2715
- ⁴Amal Abeysinghe, Julia Whitmire, Daniel Nesthus, Jeffery Moe, and Gene Stuczynski, "QTD II (Quiet Technology Demonstrator II) Main Landing Gear Noise Reduction Fairing Design and Analysis," *13th AIAA/CEAS Aeroacoustics Conference*, May 2007, Rome, Italy. AIAA 2007-3456.
- ⁵Stephen M. Jaeger, Nathan J. Burnside, Paul T. Soderman, W. Clifton Horne, and Kevin D. James, "Microphone Array Assessment of an Isolated, 26%-Scale, High Fidelity Landing Gear," *8th AIAA/CEAS Aeroacoustics Conference and Exhibit*, Breckenridge, CO, June 2002. AIAA 2002-2410
- ⁶W. Clifton Horne, Kevin D. James, Thomas K. Arledge, Paul T. Soderman, Nathan Burnside, and Stephen M. Jaeger, "Measurements of 26%-scale 777 Airframe Noise in the NASA Ames 40- by 80 Foot Wind Tunnel," *11th AIAA/CEAS Aeroacoustics Conference and Exhibit*, Monterey, CA, May 2005. AIAA 2005-2810
- ⁷Ronen Elkoby, Leon Brusniak, Robert W. Stoker, Mehdi R. Khorrami, Amal Abeysinghe, and Jefferey W. Moe., "Airframe Noise Test Results from the QTD II Flight Test Program," *13th AIAA/CEAS Aeroacoustics Conference*, May 2007, Rome, Italy. AIAA 2007-3457.
- ⁸William M. Humphreys, Jr., Qamar A. Shams, Sharon S. Graves, Bradley S. Sealey, Scott M. Bartram, and Toby Comeaux, "Application of MEMS Microphone Array Technology to Airframe Noise Measurements," *11th AIAA/CEAS Aeroacoustics Conference and Exhibit*, Monterey, CA, May 2005. AIAA 2005-3004.
- ⁹Benjamin S. Smith, Hugo E. Camargo, Ricardo A. Burdisso, and William J. Devenport, "Development and Testing of a Novel Acoustic Wind Tunnel Concept," *11th AIAA/CEAS Aeroacoustics Conference and Exhibit*, Monterey, CA, May 2005. AIAA 2005-3053
- ¹⁰William M. Humphreys Jr., Carl H. Gerhold, Allan J. Zuckerwar, Gregory C. Herring, and Scott M. Bartram, "Performance Analysis of a Cost-Effective Electret Condenser Microphone Directional Array," *9th AIAA/CEAS Aeroacoustics Conference and Exhibit*, Hilton Head, SC, May 2003. AIAA 2003-3195.
- ¹¹Thomas Mueller (ed.), *Aeroacoustic Measurements*, Springer, 2002. ISBN 3-540-41757-5.
- ¹²Marianne Mosher, "Phased Arrays for Aeroacoustic Testing: Theoretical Development," 2nd AIAA/CEAS Aeroacoustics Conference, State College, PA, May 1996. AIAA 1996-1713
- ¹³Thomas F. Brooks and William M. Humphreys, Jr., "Effect of Directional Array Size on the Measurement of Airframe Noise Components," 5th AIAA/CEAS Aeroacoustics Conference, Bellevue, WA, May 1999. AIAA 99-1958
- ¹⁴Stephen M. Jaeger, W. Clifton Horne, and Christopher S. Allen, "Effect of Surface Treatment on Array Microphone Self-Noise," *6th AIAA/CEAS Aeroacoustics Conference and Exhibit*, Lahaina, HI, June 2000. AIAA-2000-1937
- ¹⁵Marcel C. Remillieux, *Aeroacoustic Study of a Model-Scale Landing Gear in a Semi-Anechoic Wind-Tunnel*, Master thesis, Mechanical Engineering Department, Virginia Polytechnic Institute and State University, Blacksburg, VA, March 2007.